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Grain yield and carbon sequestration potential of post monsoon sorghum cultivation in Vertisols in the semi arid tropics of central India[☆]

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ABSTRACT

Soil fertility management and water conservation strongly impact soil quality and agronomic production of Vertisols. Thus the data from a 22-year of soil fertility management experiment conducted in semi arid tropical region of central India was used to evaluate the impact of input of crop residue carbon (C) through sorghum (*Sorghum bicolor* L.) cultivation in post monsoon season in Vertisols. In addition, the use of chemical fertilizers and manuring on crop yield sustainability and soil organic carbon (SOC) sequestration was assessed to 1-m depth. Retention of crop residues of sorghum, and application of farmyard manure (FYM) equivalent to 25 kg N ha^{-1} along with 25 kg N ha^{-1} supplied through chemical fertilizers increased and maintained the SOC stock. Green leaf manuring with *Leucaena* clippings along with chemical fertilizers did not increase the SOC stock. However, a conjunctive use of crop residues and *Leucaena* clippings increased the profile SOC stock (68.5 Mg ha^{-1}), an overall SOC build up (39.8%) and a high amount of SOC sequestration (14.4 Mg C ha^{-1}). These parameters were positively correlated with cumulative C input and also reflected in the sustainable yield index (SYI). Higher grain yield (1.19 Mg ha^{-1}) through the application of 25 kg N (CR) + 25 kg N (*Leucaena*) was obtained. For every Mg increase in SOC stock in the root zone there was 0.09 Mg ha^{-1} increase in grain yield of sorghum. Stabilization of the SOC stock (zero change under cropping) requires a minimum input of 1.1 Mg C ha^{-1} year^{-1}. Application of 50 kg N ha^{-1} through chemical fertilizer also maintained the SOC stock at the antecedent SOC level. Therefore, a combined use of organic manure (crop residues and FYM) or green leaf manure along with chemical fertilizer is essential to enhancing SOC sequestration in sorghum cultivation in Vertisols during the post monsoon season in central India.

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1. Introduction

Information on strategies for enrichment of soil organic carbon (SOC) stocks through sequestration of atmospheric C in agricultural soils is gaining importance because of its impacts on climate change mitigation and benefits to crop productivity and sustainability. The objective of sustainable agriculture is to adopt productive and profitable farming systems which also conserve the natural resource base, protect the environment, and enhance soil quality in a long term perspective. An optimal level of SOC can be managed through adoption of an appropriate crop rotation (Wright and Hons, 2005), judicious management of soil fertility through combination of inorganic fertilizers and organic amendments (Majumder et al., 2008; Mandal et al., 2007; Schuman et al., 2002), and use of suitable tillage methods (Lal, 2009). Soils in rain-deficit environments of the tropical and sub-tropical regions are inherently low in SOC, and agronomic yield is strongly related to soil quality. Therefore, reversing the declining trend of SOC stock is essential to enhancing agronomic productivity through balanced application of plant nutrients (i.e., N, P, K, S, Zn, Mo) and application of biomass-C.

A continuous cropping can adversely affect the distribution and stability of soil aggregates and also reduce the SOC stock (Kong et al., 2005). The magnitude of reduction in SOC stock by cropping, however, depends upon the climatic conditions and intensity of cropping (Lal, 2004). The rate of decomposition/mineralization of SOC stock is generally high in the tropics than in temperate regions (Jenkinson and Ayanaba, 1977). Nonetheless, crop species also play an important role in maintaining SOC stock through differences in quality and quantity of the residues returned which determine the mean residence time (MRT) of SOC stock (Mandal et al., 2007). Within a specific cropping system, the duration and timing of “fallowing” can also affect the SOC

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stock (Halvorson et al., 2002). The research information concerning the effect of intensive cultivation with diverse cropping systems and a range of management practices on SOC stock is scanty, especially in soils of the semi arid tropics (Lal, 2004; 2010; Velayutham et al., 2000). Once the pathways of SOC sequestration are identified, recommended agricultural practices (RMPs) may be adopted to enhance SOC stocks, reduce the net CO_2 loading into the atmosphere, and mitigate global warming (Lal, 2009). Whereas some research has been conducted in the Indian sub continent (Majumder et al., 2007; Mandal et al., 2007), most of these experiments have been done under irrigated conditions. A little, if any, research has been done under semiarid rainfed conditions, where drought stress, high temperatures and low biomass are common features. Furthermore, most of the crop management impact studies on SOC sequestration are done for the surface 0.15 to 0.2 m depth (Paustian et al., 1997).

Organic by-products from different sources can be recycled, and put to restorative use for sustaining agronomic productivity and enhancing the SOC stock. The greatest challenge of the 21st century is to feed the ever increasing world population. Although, the use of mineral fertilizers is important to addressing this challenge, hidden C costs (HCCs) of chemical fertilizers are high. Thus, it is important to use renewable sources of plant nutrients (i.e., organic materials and biofertilizers) along with chemical fertilizers. India produces about 185 Tg (Tg = teragram, 10^{12} g = 1 million metric ton) of crop residues, of which about one-third is available for recycling on arable lands (Deshpande et al., 2007; Lal, 2005). Recycling of organic residues is the highest priority toward an attempt to adopt an environmentally sound and sustainable agriculture. Use of chemical fertilizers in rainfed cropping is meager because of the prohibitively high cost and low use efficiency under harsh climatic conditions. It is thus imperative to use different organic manures and minimize the rate of application of chemical fertilizers to maintain high soil quality. Because the nutrients recycled in available low amounts of crop residues are not enough to obtain the desired level of high crop yields, a judicious use of inorganic fertilizers is also necessary to meet the nutrient requirements for increasing production of rainfed crops.

Rainfed cropping is practiced on 1.132 billion ha globally (Biradar et al., 2009), and meets about 60% of the food and nutritional needs of the world's population. The rainfed cropland areas are high in USA, Russia, China, Brazil and India. The rainfed cropping in India is practiced on 80 million ha (Mha), mostly in arid, semi-arid and sub-humid climatic zones and constitutes about 57% of the net cultivated area. Low and erratic rainfall, degraded soils and poor infrastructure are among the principal constraints in the rainfed areas of India. Vertisols, around 70 Mha in India, are the most predominant soils of these regions. Vertisols and associated soils also occur in Australia (70.5 Mha), Sudan (40 Mha), Chad (16.5 Mha) and Ethiopia (10 Mha). These five countries contain over 80% of the global area (250 Mha) of Vertisols (Virmani et al., 1989). In regions with post-monsoon cropping, soil is kept fallow during the rainy season, and used primarily for conservation of soil water and in-situ decomposition of crop residues. Similar to Vertisols in Africa, those in India are also characterized by low SOC and N concentrations. Thus, intensive cropping of these soils requires a careful management of soil temperature and moisture regimes, and use of integrated nutrient management (INM) based on combined use of manuring and chemical fertilizers. A survey of SOC concentration, conducted at 21 locations across rainfed regions of tropical India and involving eight production systems, showed that these soils are low in SOC concentration (<5 g kg^{-1}) and profile-based SOC stocks of 20.4 to 96.9 Mg ha^{-1} (Srinivasarao et al., 2009). Therefore, maintaining soil and crop productivity over the long term under continuous monocropping is the major challenge of rainfed cropping on Vertisols in south-central India. Low agronomic yields, low or no retention of crop residues, and long fallow periods of up to 7 months per year involving uncontrolled grazing decrease the SOC concentration and stock. However, the change in SOC stock by cropping depends on the balance between the loss of C by tillage-induced mineralization, the quantity and quality of crop residues returned, and the biomass-C applied to the soils. Therefore, crop and soil management practices must be designed to ensure long term sustainability. Recycling of plant nutrients through use of organic amendments and the inclusion and incorporation of leguminous cops in the rotation cycle are important to sustainability. Sorghum (*Sorghum bicolor*) is an important cereal grown in the post monsoon season in south-central India. Resource-poor and small-size land holders depend on the productivity and sustainability of sorghum.

Thus, this study was aimed at assessing the effects of 22 years of cropping, use of chemical fertilizers and organics on complementary basis on SOC sequestration in Vertisols, establish the relationship between SOC sequestration and sustainable yield index (SYI) in long term manurial trials, and determine the requirement of critical inputs of biomass-C for stabilizing (zero change) the SOC stock.

2. Materials and methods

2.1. Site description

A long-term field experiment with post monsoon sorghum monocropping on a medium Vertisol (*Vertic Ustropept*) was carried out at the Dry Farming Research Station, Solapur, Maharashtra, India. The site is located at 75°32′E longitude and 17°51′ N latitude, at 480 m mean sea level in the semi arid (dry), tropical region (AESR 6.1). The experiment, initiated in the post rainy season of 1985, was conducted under the aegis of the All India Coordinated Research Project on Dryland Agriculture (AICRPDA). For the 22-year duration of the experiment (1985–2007), the mean maximum and minimum annual air temperatures were 32.3 °C and 22.3 °C, respectively, and the mean annual precipitation was poorly distributed and 723 mm, the annual potential evapotranspiration (PET) was 1856 mm, and the frequency of 61% water deficit drought was once in 10 years. Total annual rainfall and that received during the cropping season over the 22 year experimental period are depicted in Fig. 1. Length of growing period at this site varies between 90 and 120 days.

Soil of the experimental site is clayey in texture, alkaline in reaction (pH 8.0), and has a low profile SOC concentration (3.5 g kg^{-1} soil), low available N (103 kg ha^{-1}) and available P (9.6 kg ha^{-1}) and high available K (596 kg ha^{-1}) contents. Sand, silt and clay contents are 13.3, 12.0 and 74.7%, respectively. It has soil inorganic carbon (SIC) concentration of 4.5 g kg^{-1} and cation exchange capacity (CEC) of 36.7 C mol (P^{+}) kg^{-1}.

2.2. Treatments and crop management

Sorghum (variety: M35-1) was grown every year in the post rainy season (from second week of September to last week of February)

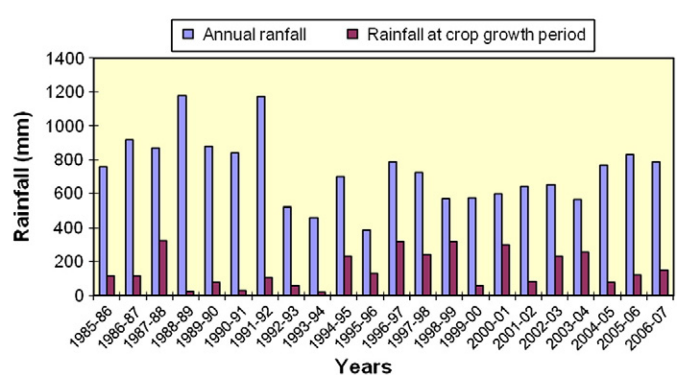

Fig. 1. Mean annual and seasonal rainfall between 1985 and 2007.

during the 22 year period (1985–2007). The experiment was laid out in a randomized block design with the following treatments:

i. T_1 = Control (no N–P–K fertilizers or organics),
ii. T_2 = 25 kg N ha^{-1} as urea,
iii. T_3 = 50 kg N ha^{-1} as urea,
iv. T_4 = 25 kg N ha^{-1} through farmyard manure (FYM) + 25 kg N ha^{-1} as urea,
v. T_5 = 25 kg N ha^{-1} through crop residues (CR) as sorghum stover + 25 kg N ha^{-1} as urea,
vi. T_6 = 25 kg N ha^{-1} through *Leucaena* clippings + 25 kg N ha^{-1} as urea, and
vii. T_7 = 25 kg N ha^{-1} through crop residues (CR) as sorghum stover + 25 kg N ha^{-1} through *Leucaena* clippings.

The gross and net plot sizes were 11.7 × 10.0 m and 9.9 × 8.2 m, respectively, and each treatment was replicated four times. To supply N equivalent to 25 kg ha^{-1}, the organic materials (i.e. sorghum stover, farmyard manure and *Leucaena* clippings) were incorporated in the soil with a wooden plow during June to July every year depending on the rainfall. Average annual addition of sorghum crop residue (4.9 g kg^{-1} N), farm yard manure (5.6 g kg^{-1} N) and *Leucaena* clippings (23.2 g kg^{-1} N) were 5.1, 4.5 and 1.1 Mg ha^{-1} with C:N ratios of 89.0:1, 59.1:1 and 11.2:1, respectively. Application of N as urea as per treatments and P at 25 kg P_2O_5 ha^{-1} to all the treatments were made at the time of sowing of the post rainy season sorghum. The added organic materials were better decomposed through the rainfall received during the rainy season. Soil was harrowed prior to sowing, and sorghum was seeded by a seed drill. Manual weeding was done via an intercultural operation as and when needed. Crop was harvested soon after maturity in the last week of February and the above-ground biomass was removed. Grain and stover yields of sorghum were recorded every year, and grain yield data is reported as mean of the years. Moisture contents of grains and stover were determined. Grain yield was expressed at 14% moisture level.

2.3. Soil sampling and analysis

Three representative field-moist soil samples were collected with a tube auger at 0.2 m increments down to 1-m depth during April 2007 from each plot in every replication. Soil samples were pooled together to make a composite sample for each depth and replication. Additionally, three samples were taken from all five depths using a core sampler (0.05 m in diameter, 0.08 m in length) to measure soil bulk density (Blake and Hartge, 1986).

2.4. Total organic carbon

Soil samples were air dried, gently ground, and passed through a 2-mm sieve. A part of the sample was finely ground and passed through a 0.2-mm sieve. Simultaneously, the particulate organic matters (i.e., FYM, sorghum crop residues, *Leucaena* clippings, sorghum stubbles and roots) were oven dried and finely ground in a mechanical grinder (Nelson and Sommers, 1982). These samples were analyzed for C concentration by a LECO CHN analyzer. Soil samples were also analyzed for SIC concentration titrimetrically, by digesting them with dilute HCl (Bundy and Bremner, 1972). Total SOC concentration was estimated by Eq. (1).

$$\mathrm{SOC} = \mathrm{LECO\ C} - \mathrm{HClC}. \tag{1}$$

2.5. Profile SOC stock

The total SOC stock of the profile expressed as Mg ha^{-1} for each of the five depths (0–0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8, and 0.8–1.0 m) was computed by multiplying the SOC concentration (g kg^{-1}) (obtained by SOC = LECO C–HCl C) by the bulk density (Mg m^{-3}) and depth (m), and by 10.

2.6. Carbon inputs through plant and organic materials

Based on biomass yield of sorghum, annual C inputs to the soil through stubbles, roots and rhizodeposition were computed. Sorghum stubbles constituted 6.6, 6.8, 7.1, 7.6, 7.4, 7.6 and 7.3% of the stover yield of sorghum in the plots under Control, 25 kg N (urea), 50 kg N (urea), 25 kg N (FYM) + 25 kg N (urea), 25 kg N (CR) + 25 kg N (urea), 25 kg N (*Leucaena*) + 25 kg N (urea) and 25 kg N (CR) + 25 kg N (*Leucaena*), respectively. The root biomass was calculated using the root:shoot biomass ratios recorded from the experiments. Root biomass was measured immediately after harvesting the crop, following the core-sampling procedure as described by Franzluebbers et al. (1999). It was estimated that the root biomass represented 30.6, 29.3, 28.5, 26.1, 26.4, 25.9 and 25.7% of the stover biomass in the plots in the treatments listed above, respectively. Rhizodeposition of C from root turnover and exudates was assumed to be 1.4 times of the root C of sorghum (Shamoot et al., 1968). Stubbles and roots contain 436 g kg^{-1} and 394 g kg^{-1} C, respectively. During the growth of the crop, weeds were either removed or killed with herbicides and so C inputs from roots and rhizodeposition by the weeds were not considered. Using all the measurements described above, a treatment-wise estimate of plant derived C inputs, as well as C inputs through organics applied to the soil, are presented in Table 1. The highest mean annual C inputs through crop residues and organic material were added in 25 kg N (CR) + 25 kg N (*Leucaena*) (3.4 Mg ha^{-1} $year^{-1}$), followed by 25 kg N (CR) + 25 kg N (urea) (3.0 Mg ha^{-1} $year^{-1}$), 25 kg N (FYM) + 25 kg N (urea) (2.3 Mg ha^{-1} $year^{-1}$) and the lowest was in control (0.6 Mg ha^{-1} $year^{-1}$).

2.7. Calculations for C budgeting

$$\mathrm{C\ build-up}(\%) = \frac{C_{fert+org}\ or\ C_{fert} - C_{cont}}{C_{cont}} \times 100 \tag{2}$$

where $C_{fert+org}$ represents profile SOC stock in fertilizer N (urea) + FYM/CR/*Leucaena* clippings treatments and C_{fert} and C_{cont} are the profile SOC stock in fertilizer N (urea) and control treatments, respectively.

$$\mathrm{C\ build-up\ rate}\left(\mathrm{Mg\ C\ ha^{-1} year^{-1}}\right) = \frac{C_{fert+org}\ C_{fert} - C_{cont}}{Years\ of\ experimentation} \tag{3}$$

$$\mathrm{C\ stabilization}(\%) = \frac{C_{fert+org} - C_{fert}}{C_{org}} \times 100 \tag{4}$$

where C_{org} represent C applies through organic material (FYM/CR/*Leucaena* clippings)

$$\mathrm{C\ sequestered}\left(\mathrm{Mg\ C\ ha^{-1}}\right) = \mathrm{SOC_f} - \mathrm{SOC_i} \tag{5}$$

where SOC_f and SOC_i indicate the SOC stocks in 2007 (current) and that at the initiation of the long-term experiment (in 1985). Positive and negative values indicate SOC gains and losses, respectively.

2.8. Sustainable yield index (SYI)

The total sorghum crop productivity was calculated through a sustainable-yield index (SYI) using yield-data of 22 years. This was done to offset annual variations in the yield, and to highlight the performance of the treatments, during the entire experimental period. The sustainable yield index is defined as per Eq. (6)

$$\mathrm{SYI} = \frac{Y - \sigma}{Ym} \tag{6}$$

Table 1
Mean (1985–2007) annual C input to soil from rainfed sorghum under different fertilizer and manurial treatments.

Treatment	SYI	Mean annual C input ($Mg\ ha^{-1}$)						Cumulative C input in 22 years ($Mg\ ha^{-1}$)		
		Stubble	Root	RD	Total crop residue C input	C input through organics	Total annual C input	Through crop residue	Through organics	Total
Control	0.38^{D}	0.05	0.22	0.31	0.59^{E}		0.59	12.9	0.0	12.9^{F}
25 kg N (urea)	0.40^{C}	0.08	0.29	0.41	0.78^{C}		0.78	17.2	0.0	17.2^{E}
50 kg N (urea)	0.41^{C}	0.09	0.33	0.46	0.87^{B}		0.87	19.2	0.0	19.2^{D}
25 kg N (FYM) + 25 kg N (urea)	0.44^{B}	0.10	0.31	0.44	0.85^{B}	1.48	2.33	18.7	32.5	51.2^{C}
25 kg N (CR) + 25 kg N (urea)	0.45^{B}	0.09	0.29	0.41	0.80^{C}	2.22	3.02	17.6	48.9	66.5^{B}
25 kg N (*Leucaena*) + 25 kg N (urea)	0.44^{B}	0.08	0.24	0.33	0.65^{D}	0.28	0.93	14.2	6.2	20.4^{D}
25 kg N (CR) + 25 kg N (*Leucaena*)	0.48^{A}	0.10	0.33	0.46	0.90^{A}	2.50	3.40	19.7	55.1	74.8^{A}

SYI, sustainable yield index; RD, rhizodeposition; FYM, farmyard manure; CR, sorghum crop residue.
Different letters within columns are significantly different at P = 0.05 according to Duncan Multiple Range Test (DMRT) for separation of means.

where Y is the estimated average yield of a practice across the years. σ is its estimated standard deviation, and Ym is the observed maximum yield in the experiment during the years of cultivation (Singh et al., 1990).

2.9. Statistical analysis

Statistical analysis was performed using the Windows based SPSS program (SPSS, 2001) (Version 11.0, SPSS, Chicago, IL). The SPSS procedure was used to analyze variance and to determine the statistical significance of treatment effects. The Duncan Multiple-Range-Test was used to compare treatment means. Simple correlation coefficients and regression equations were also developed to evaluate the relationships among the response variables (SYI, C inputs, profile SOC, C build up and C sequestration) using the same statistical package. Experimental means were compared at the 95% probability level.

3. Results and discussion

3.1. Carbon input levels, yield and sustainability

Estimates of the component wise (stubble, root and rhizodeposition) as well as external inputs through FYM/CR/*Leucaena* clippings cumulative C inputs into soil under different treatments during the 22 years of continuous cropping are given in Table 1. The cumulative C input ranged from 12.9 $Mg\ C\ ha^{-1}$ in the control to 74.8 $Mg\ C\ ha^{-1}$ in the 25 kg N (CR) + 25 kg N (*Leucaena*) treatment. Complementary use of organic materials along with fertilizer or application of equivalent amount of 50 kg N ha^{-1} completely through organic material (crop residue and *Leucaena*) produced higher biomass and subsequently higher C input in terms of crop residues (0.9–3.4 $Mg\ C\ ha^{-1}\ year^{-1}$) compared with control (0.6 $Mg\ C\ ha^{-1}\ year^{-1}$) and N application through chemical fertilizers. Treatments comprised of FYM/CR/*Leucaena* green leaf manure addition received the extra 0.3–2.5 $Mg\ C\ ha^{-1}\ year^{-1}$ in the form of organic materials.

Grain yield of sorghum increased significantly with different fertilizer and manurial treatments compared with control ($P<0.05$) (Table 2). However, grain yield did not differ among treatments for the initial 2 to 3 years. Subsequently, consistently higher yields were obtained with the use organic in combination with chemical fertilizer than control. For the entire 22 year period, higher grain yield was obtained through the application of 25 kg N (CR) + 25 kg N (*Leucaena*) (1.2 $Mg\ ha^{-1}$), and it was on par with 25 kg N (FYM) + 25 kg N (urea) (1.06 $Mg\ ha^{-1}$), 25 kg N (CR) + 25 kg N (urea)(1.05 $Mg\ ha^{-1}$) and 50 kg N (urea) (1.04 $Mg\ ha^{-1}$) and was the least in control (0.61 $Mg\ ha^{-1}$). Beneficial effect of application of organic materials as a source of N on sorghum grain yield was earlier reported by Bellaki and Badanur (2000). Under rainfed conditions, farm yields are usually influenced by seasonal

Table 2
Grain yields ($Mg\ ha^{-1}$) of post monsoon sorghum between 1985 and 2007.

Year	Control	25 kg N (urea)	50 kg N (urea)	25 kg N (FYM) + 25 kg N (urea)	25 kg N (CR) + 25 kg N (urea)	25 kg N (*Leucaena*) + 25 kg N (urea)	25 kg N (CR) + 25 kg N (*Leucaena*)	Mean	CD (p = 0.05)
1985–86	0.85	1.11	1.47	1.36	1.05	1.18	1.69	1.24	0.10
1986–87	0.15	0.23	0.22	0.21	0.23	0.21	0.31	0.22	0.02
1987–88	0.60	1.00	1.19	1.25	1.00	0.81	1.12	1.00	0.08
1988–89	0.84	0.94	1.03	1.07	1.11	1.11	1.18	1.04	0.08
1989–90	0.63	0.79	0.89	0.87	0.82	0.87	0.92	0.83	0.07
1990–91	0.74	1.23	1.42	1.40	1.29	1.01	1.59	1.24	0.10
1991–92	0.83	0.91	1.04	1.17	0.87	1.12	1.31	1.04	0.08
1992–93	0.80	0.98	1.01	1.02	0.98	1.05	1.10	0.99	0.08
1993–94	0.65	1.26	1.66	1.65	1.26	0.88	1.30	1.24	0.10
1994–95	0.84	1.08	1.03	0.91	1.33	1.11	1.44	1.10	0.09
1995–96	0.47	0.58	1.13	1.03	1.04	0.65	1.09	0.85	0.07
1996–97	0.67	1.32	1.61	1.47	1.71	0.92	1.41	1.30	0.10
1997–98	0.11	0.19	0.24	0.20	0.18	0.15	0.24	0.19	0.01
1998–99	0.61	0.89	1.04	1.06	1.05	0.85	1.19	0.96	0.08
1999–00	0.86	1.02	1.16	1.05	1.43	0.88	1.09	1.07	0.09
2000–01	0.74	0.94	1.03	1.21	1.20	0.84	1.31	1.04	0.08
2001–02	0.55	1.16	1.24	1.31	1.16	0.73	1.00	1.02	0.08
2002–03	0.55	0.83	0.99	1.00	0.99	0.79	1.13	0.90	0.07
2003–04	0.67	0.95	1.10	1.12	1.11	0.91	1.25	1.01	0.08
2004–05	0.34	0.67	0.70	0.75	1.13	0.75	1.50	0.83	0.07
2005–06	0.35	0.58	0.66	0.92	0.85	0.74	1.38	0.78	0.06
2006–07	0.56	1.01	1.12	1.32	1.27	1.09	1.55	1.13	0.09
Mean	0.61	0.89	1.04	1.06	1.05	0.85	1.19		

Table 3
Changes in soil organic carbon (SOC) concentration (g kg^{-1}) in soil sampled in 2007 (±standard deviation from mean).

Treatment	Depth (m)					Mean
	0–0.2	0.2–0.4	0.4–0.6	0.6–0.8	0.8–1.0	
Initial SOC	4.7 ± 0.26	4.5 ± 0.25	3.5 ± 0.19	2.8 ± 0.15	2.1 ± 0.12	3.5 ± 0.19
Control	4.5 ± 0.25^{Da}	3.9 ± 0.21^{Db}	3.2 ± 0.18^{Cc}	2.4 ± 0.13^{Cd}	1.9 ± 0.10^{Be}	3.2 ± 0.17^{D}
25 kg N (urea)	4.9 ± 0.27^{Ca}	4.6 ± 0.25^{Cb}	3.2 ± 0.18^{Cc}	2.3 ± 0.13^{Cd}	1.9 ± 0.10^{Be}	3.4 ± 0.19^{C}
50 kg N (urea)	5.3 ± 0.29^{Ba}	4.8 ± 0.26^{Cb}	3.3 ± 0.18^{Cc}	2.4 ± 0.13^{Cd}	1.8 ± 0.10^{Be}	3.5 ± 0.19^{C}
25 kg N (FYM) + 25 kg N (urea)	5.4 ± 0.30^{Ba}	5.2 ± 0.29^{Ba}	4.5 ± 0.25^{Bb}	3.2 ± 0.18^{Ac}	2.2 ± 0.12^{Ad}	4.1 ± 0.23^{B}
25 kg N (CR) + 25 kg N (urea)	5.8 ± 0.32^{Aa}	5.7 ± 0.31^{Aa}	5.1 ± 0.28^{Ab}	2.8 ± 0.15^{Bc}	2.1 ± 0.12^{Ad}	4.3 ± 0.24^{A}
25 kg N (*Leucaena*) + 25 kg N (urea)	5.4 ± 0.30^{Ba}	4.6 ± 0.25^{Cb}	3.3 ± 0.18^{Cc}	2.4 ± 0.13^{Cd}	1.8 ± 0.10^{Be}	3.5 ± 0.19^{C}
25 kg N (CR) + 25 kg N (*Leucaena*)	5.9 ± 0.32^{Aa}	5.8 ± 0.32^{Aa}	5.1 ± 0.28^{Ab}	3.4 ± 0.19^{Ac}	2.3 ± 0.13^{Ad}	4.5 ± 0.25^{A}
Mean	5.3 ± 0.29^{a}	4.9 ± 0.27^{b}	4.0 ± 0.22^{c}	2.7 ± 0.15^{d}	2.0 ± 0.11^{e}	

Different capital letters within columns and different small letters within rows are significantly different at P = 0.05 according to Duncan Multiple Range Test (DMRT) for separation of means.

Table 4
Change in soil bulk density (Mg m^{-3}) in the experimental plot in relation to cropping, fertilization and manuring treatments (± standard deviation from mean).

Depth (m)	Initial (1985)	At the end of experiment (in 2007)						
		Control	25 kg N (urea)	50 kg N (urea)	25 kg N (FYM) + 25 kg N (urea)	25 kg N (CR) + 25 kg N (urea)	25 kg N (*Leucaena*) + 25 kg N (urea)	25 kg N (CR) + 25 kg N (*Leucaena*)
0–0.2	1.50 ± 0.06	1.51 ± 0.07^{Ad}	1.51 ± 0.07^{Ad}	1.51 ± 0.06^{Ad}	1.49 ± 0.06^{Be}	1.49 ± 0.06^{Be}	1.49 ± 0.06^{Be}	1.48 ± 0.06^{Cd}
0.2–0.4	1.53 ± 0.07	1.54 ± 0.08^{Ac}	1.53 ± 0.08^{Bc}	1.53 ± 0.07^{Bc}	1.51 ± 0.07^{Dd}	1.52 ± 0.07^{Cd}	1.52 ± 0.07^{Cd}	1.50 ± 0.07^{Ec}
0.4–0.6	1.55 ± 0.08	1.55 ± 0.08^{Ab}	1.55 ± 0.08^{Ab}	1.55 ± 0.08^{Ab}	1.55 ± 0.08^{Ac}	1.55 ± 0.08^{Ac}	1.55 ± 0.08^{Ac}	1.54 ± 0.08^{Bb}
0.6–0.8	1.57 ± 0.09	1.57 ± 0.09^{Aa}	1.57 ± 0.09^{Aa}	1.57 ± 0.09^{Aa}	1.56 ± 0.08^{Bb}	1.57 ± 0.09^{Aa}	1.56 ± 0.08^{Bb}	1.57 ± 0.09^{Aa}
0.8–1.0	1.57 ± 0.09	1.57 ± 0.09^{Aa}	1.57 ± 0.09^{Aa}	1.57 ± 0.09^{Aa}	1.57 ± 0.09^{Aa}	1.56 ± 0.08^{Bb}	1.57 ± 0.09^{Aa}	1.57 ± 0.09^{Aa}

Different capital letters within rows and different small letters within columns are significantly different at P = 0.05 according to Duncan Multiple Range Test (DMRT) for separation of means.

rainfall particularly the amount received at critical growth stages of the crop. In the present study, grain yield of sorghum significantly and positively correlated with rainfall received in September ($r = 0.81^*$, $P < 0.05$) and October ($r = 0.83^*$, $P < 0.05$).

Application of chemical fertilizers alone did not sustain agronomic productivity on long term basis. Application of 25 kg N (CR) + 25 kg N (*Leucaena*) produced significantly higher grain yield compared with the unfertilized control. Similarly, significantly higher SYI was obtained with the application of organics either alone or in combination with chemical fertilizers compared to control or sole application of chemical fertilizers. Highest SYI was obtained with 25 kg N (CR) + 25 kg N (*Leucaena*) (0.48) followed by 25 kg N (CR) + 25 kg N (urea) (0.45) and the lowest in control (0.38) (Table 1). A higher SYI was also obtained with use of FYM or *Leucaena* clippings along with urea which was at par with 25 kg N (CR) + 25 kg N (urea) treatment. This trend is mainly due to resilience of soil system to intermittent droughts with high moisture retention capacity in plots receiving organic amendments compared with those receiving inorganic fertilizers. This response underlines the importance of organics in enhancing soil resilience under harsh climatic conditions during the cropping period, a common feature of rainfed agriculture (Srinivasarao et al., 2011).

3.2. Depth distribution of organic carbon

The SOC concentration differed significantly ($P < 0.05$) among treatments and depths (Table 3). The highest SOC concentration of 5.9 g kg^{-1} in the surface layer (0–0.2 m) was observed in the 25 kg N (CR) + 25 kg N (*Leucaena*) followed by that in the 25 kg N (CR) + 25 kg N (urea) (5.8 g kg^{-1}) treatment. All plots treated with organic amendments contained higher SOC concentration in the surface and sub-soil compared with those not receiving any organics. The SOC concentration also improved with the application of 50 kg N ha^{-1} (5.3 g kg^{-1}) and 25 kg N ha^{-1} (4.9 g kg^{-1}) as urea. In contrast, sorghum cultivation without any fertilizer or manuring over 22 years reduced SOC concentration, while application of chemical fertilizers maintained the profile SOC concentration. In contrast, the SOC concentration increased with the application of organic materials even in the sub-soil. The mean profile SOC concentration increased from 3.2 g kg^{-1} in control to 4.5 g kg^{-1} in 25 kg N (CR) + 25 kg N (*Leucaena*). However, no increase in SOC concentration was observed in treatment receiving 25 kg N (*Leucaena*) + 25 kg N (urea). It is widely recognized that the use of organic manures and compost enhances the SOC concentration more than does the use of the same amount of nutrients applied as chemical fertilizers (Gregorich et al., 2001). However, the use of green leaf manuring with *Leucaena* clippings (C:N ratio of 11.2:1) contributed low amount of C input, with a higher C mineralization in tropical semi arid conditions, and caused a low SOC sequestration.

3.3. Soil bulk density

The depth-wise bulk density (BD) of the experimental soil before the initiation of the long term experiment, and the treatment-wise values at the end of the experiment are presented in Table 4. With organic amendments, soil BD was lower than with mineral fertilization and unfertilized control. The lowest BD was observed in surface layer (0–0.2 m) under 25 kg N (CR) + 25 kg N (*Leucaena*) (1.48 Mg m^{-3})

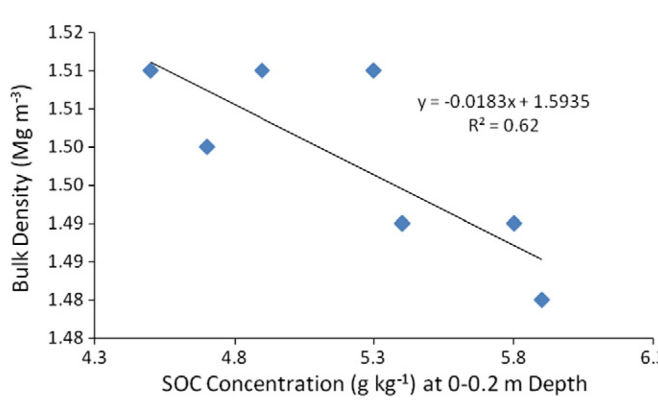

Fig. 2. Influence of SOC concentration on bulk density of soils.

Table 5
The profile SOC stock, % increase in SOC stock, rate of SOC sequestration and the total amount of SOC for different fertilization treatments under semiarid conditions (± standard deviation from mean).

Treatment	Profile SOC ($Mg\ ha^{-1}$)	Increase in SOC (%)	Rate of SOC sequestration ($Mg\ C\ ha^{-1}\ year^{-1}$)	Total SOC Sequestrated ($Mg\ C\ ha^{-1}$)
Control	49.0 ± 1.5^{E}	–	–	-5.1 ± 0.32^{F}
25 kg N (urea)	52.0 ± 1.6^{D}	6.1 ± 0.4^{E}	0.14 ± 0.01^{E}	-2.1 ± 0.13^{E}
50 kg N (urea)	54.1 ± 1.7^{D}	10.4 ± 0.6^{D}	0.23 ± 0.01^{D}	0.1 ± 0.01^{D}
25 kg N (FYM) + 25 kg N (urea)	62.6 ± 1.9^{C}	27.8 ± 1.6^{C}	0.62 ± 0.04^{C}	8.5 ± 0.54^{C}
25 kg N (CR) + 25 kg N (urea)	65.8 ± 2.0^{B}	34.3 ± 2.0^{B}	0.76 ± 0.05^{B}	11.7 ± 0.74^{B}
25 kg N (*Leucaena*) + 25 kg N (urea)	53.4 ± 1.7^{D}	9.0 ± 0.5^{D}	0.20 ± 0.01^{D}	-0.7 ± 0.04^{D}
25 kg N (CR) + 25 kg N (*Leucaena*)	68.5 ± 2.1^{A}	39.8 ± 2.3^{A}	0.89 ± 0.05^{A}	14.4 ± 0.91^{A}

Different letters within columns are significantly different at P = 0.05 according to Duncan Multiple Range Test (DMRT) for separation of means.

and the highest in control ($1.51\ Mg\ m^{-3}$) and chemical fertilizer receiving plots. Soil BD decreased with the application of organic amendments due to higher SOC concentration and increased root biomass (Halvorson et al., 1999), which resulted in better soil aeration and aggregation. There existed a negative correlation between SOC concentration in the surface 0.2 m layer and its BD (Fig. 2), as was also reported by Du et al. (2009). As expected, however, soil BD increased with increase in depth.

3.4. Profile SOC, C buildup, stabilization and sequestration

The profile SOC stock differed significantly ($P < 0.05$) among treatments (Table 5). The highest SOC stock of $68.5\ Mg\ C\ ha^{-1}$ was observed in the 25 kg N (CR) + 25 kg N (*Leucaena*) followed by that of $65.8\ Mg\ C\ ha^{-1}$ in the 25 kg N (CR) + 25 kg N (urea) > that in the 25 kg N (FYM) + 25 kg N (urea) ($62.6\ Mg\ C\ ha^{-1}$) > 50 kg N (urea) ($54.1\ Mg\ C\ ha^{-1}$) = 25 kg N (*Leucaena*) + 25 kg N (urea) ($53.4\ Mg\ C\ ha^{-1}$), and the lowest ($49.0\ Mg\ C\ ha^{-1}$) in the control. Relatively higher percentage increase of SOC stock was observed in the 25 kg N (CR) + 25 kg N (*Leucaena*) treatment (39.8%) followed by 25 kg N (CR) + 25 kg N (urea) (34.3%) and 25 kg N (FYM) + 25 kg N (urea) (27.8%). The rate of SOC sequestration also followed a trend similar to that of percentage increase of SOC stock. The data show that 32.6, 28.2 and 22.6% of biomass C input was stabilized in FYM, sorghum CR and *Leucaena* clippings, respectively. Majumder et al. (2008) reported that 67.9, 57.3 and 48.9% C input was stabilized in FYM, rice (*Oryza sativa* L.) straw and sesbania (*Sesbania sesban* L.) green manuring in a rice-wheat (*Triticum aestivum* L.) system in the Indo Gangetic plains. Higher amount of ash, lignin and polyphenol present in FYM, higher C:N ratio of sorghum CR (89.0:1) leads to a higher C stabilization compared with that for the application of *Leucaena* clippings. With the exception of control, even treatments involving a lower rate of N applied either as chemical fertilizer (25 kg N as urea) or as *Leucaena* clippings along with chemical fertilizers caused SOC sequestration ranging from 0.1 to $14.4\ Mg\ C\ ha^{-1}$. A higher SOC sequestration was observed with the combined use of CR and *Leucaena* ($14.4\ Mg\ C\ ha^{-1}$) followed by that for the 25 kg N (CR) + 25 kg N (urea) ($11.7\ Mg\ C\ ha^{-1}$) > 25 kg N (FYM) + 25 kg N (urea) ($8.5\ Mg\ C\ ha^{-1}$). Cultivation of sorghum without the application of any organics and/or inorganic fertilizers (control) depleted the SOC stock by $5.1\ Mg\ C\ ha^{-1}$. In comparison, application of $50\ kg\ N\ ha^{-1}$ as urea maintained the SOC stock, while the combined application of chemical fertilizers and *Leucaena* depleted the SOC stock by $0.7\ Mg\ C\ ha^{-1}$. Regardless of the farming system, maintaining the SOC stock above the threshold level is necessary to sustain agronomic productivity and minimize the risks of soil degradation. Thus, there existed a positive relationship between SOC stock in the root zone depth and the grain yield of sorghum ($89\ kg\ ha^{-1}\ year^{-1}\ Mg^{-1}$ of SOC). However, maintaining or improving SOC stock in the arid and semiarid regions is a major challenge. The prevailing low levels of SOC concentrations and stocks in soils of these regions in India are attributed to soil-mining practices: little or no crop residues returned to the soil, excessive tillage, imbalance in fertilizer use and severe soil degradation (Lal, 2009).

Plow-induced perturbation adversely impacts the amount and stability of soil aggregates, exacerbates the mineralization of organic matters and depletes SOC stock. While plowing-related depletion of SOC stock is widely observed, the magnitude of depletion differs among soil types, climatic regimes, crops/cropping systems, land use history, and the duration of the fallow period (Davidson and Ackerman, 1993; Guo and Gifford, 2002; Mandal et al., 2008). A higher input of biomass C through the application of $50\ kg\ N\ ha^{-1}$ as organic amendments or complementary use of organic and chemical fertilizers may be due to increased availability of essential nutrients (i.e., N, P, K, Ca, Mg, S, Zn and B)(Srinivasarao and Vittal, 2007). Annual inputs of biomass-C as crop residues and other biofertilizers significantly increased SOC sequestration and stock, following an asymptotic relationship between the SOC stock and the magnitude of the inputs of biomass C in different treatments (Fig. 3). Yet, the application of biomass decreased soil BD in the surface and subsurface layers and also increased the root biomass (Halvorson et al., 1999). There existed a strong negative correlation between SOC stock and soil BD. Similar observations were made by Du et al. (2009) ($r = 0.91^{*}$; $P < 0.05$). There was also a positive correlation between SOC stocks and magnitude of SOC sequestration, and the input of CR ($r = 0.69$; $P < 0.05$), organic amendments ($r = 0.98^{*}$; $P < 0.05$) and total C inputs ($r = 0.99^{*}$; $P < 0.05$) explaining 47 to 98% of variability (Figs. 4 and 5). Relatively higher magnitude of SOC sequestration in treatments receiving organic manure may be because of the application of decomposed material containing a higher proportion of chemically recalcitrant compounds (Paustian et al., 1992). A significant correlation between the SOC stock and the C input as CR, biofertilizers and the total C input indicates the importance of residue retention and application of biosolids to improving soil quality. Venkateswarlu et al. (2007) observed a significant improvement in SOC stock after 10 years of including horsegram (*Macrotyloma uniflorum* L.) cover crop in a cropping system established on an Alfisol under semi arid tropical conditions of central India. However, low availability of adequate quantities of organic amendments under such conditions is a major constraint

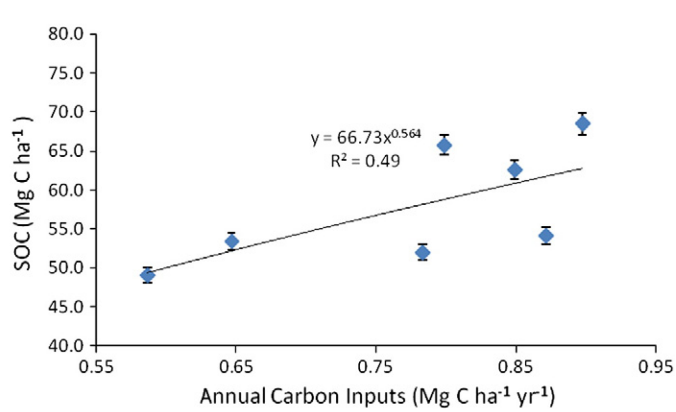

Fig. 3. Effects of input of the C in crop residues on SOC stock (SOC; error bars represents the standard error of mean).

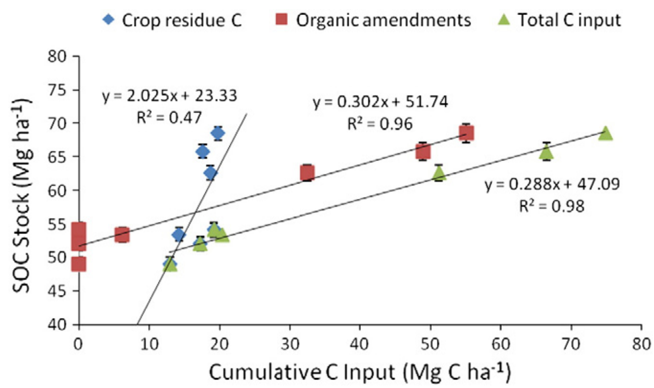

Fig. 4. Influence of cumulative carbon input through a) crop residues, b) organic amendments, and c) total carbon on soil organic carbon stock (error bars represents the standard error of mean, p = 0.05).

which is exacerbated by a lower biomass production, use of crop residues as animal feed and of animal dung as a cooking fuel.

3.5. Relationship among C inputs and sequestrated C with yield sustainability

The SYI was also in accord with the SOC, and a significant correlation existed between SYI and the total C input (r = 0.87*; R^2 = 0.76, P < 0.05), % SOC sequestration (r = 0.90*; R^2 = 0.81, P < 0.05), profile SOC stock (r = 0.90*; R^2 = 0.81, P < 0.05) and the SOC sequestered (r = 0.90*; R^2 = 0.81, P < 0.05) (Table 6). However, the correlation of SYI with the annual input of CR was weak ($R^2 = 0.31^{NS}$). Thus, the maintenance of SOC stock through application of manure and chemical fertilizers is essential to the sustainability of rainfed production systems in the semi-arid tropics. Any improvement in SOC enhances water holding capacity of the soil profile (Du et al., 2009) which alleviates frequency and intensity of drought stress.

3.6. Carbon sequestration and the critical level of C inputs

Cultivation of sorghum for 22 years in Vertisols under semi arid conditions without using any organics and/or inorganic fertilizers (control) depleted the SOC stock by −5.1 Mg C ha^{-1}. However, addition of organic manures, alone or in combination with inorganic fertilizers, significantly increased the SOC stock. The C sequestration potential (CSP), defined as the rate of increase in the SOC stock vis-à-vis the antecedent baseline stock in the 0–0.2 m depth, ranged from −0.18 Mg C ha^{-1} year^{-1}

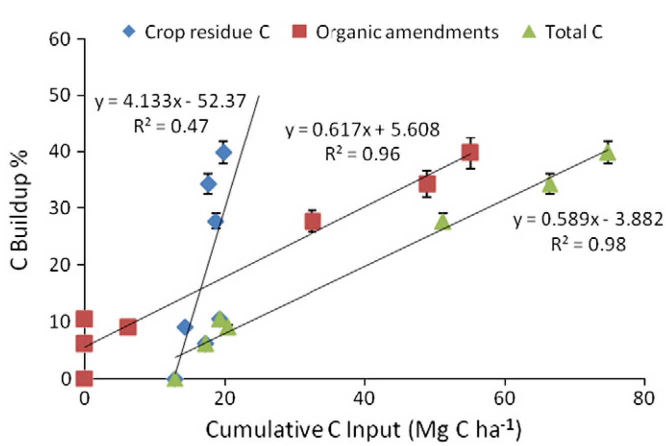

Fig. 5. Influence of cumulative carbon input through a) crop residue, b) organic amendments, and c) total carbon on SOC sequestration (error bars represents the standard error of mean, P = 0.05).

Table 6
Relationships of SYI to crop residue C input, total cumulative C input, % change in SOC stock and the magnitude of SOC sequestered after 22 years of cropping.

Parameters	Regression equation	R^2
Annual crop residue C input (X)	SYI = 0.16X + 0.30	0.31^{NS}
Total cumulative C input (X)	SYI = 0.001X + 0.39	0.76*
C buildup % (X)	SYI = 0.002X + 0.39	0.81*
Profile SOC (X)	SYI = 0.004X + 0.2	0.81*
C sequestrated (X)	SYI = 0.004X + 0.41	0.81*

* Indicates significance at P < 0.05, NS, Non significant.

(unfertilized control) to 0.57 Mg C ha^{-1} year^{-1} (50% RDF + 4 Mg ha^{-1} groundnut shells) (Bhattacharyya et al., 2009). The positive and linear correlation between changes in SOC stock and the total cumulative C inputs to the soils (external organics plus crop residue) over the years (Y = 0.29X-7.0; $R^2 = 0.98^{***}$, P < 0.001) (Fig. 6) is a strategically important information. It implies that even with 22 years of continuous input of biomass-C ranging from 0.6 to 3.4 Mg C ha^{-1} year^{-1}, the soil C sink capacity was not filled. Therefore, Vertisols have a high SOC sink capacity. Yet, the soil C sink capacity is finite (Six et al., 2002), and a different rate of C loading causes a new steady state of SOC over time. A periodic assessment of SOC stock, even at decadal intervals, may provide guidelines for sustainable management of soils. The slope of the curve (Fig. 6) represents the rate of conversion of biomass-C into SOC stock, which is about 29% for the sorghum-based cropping system. This conversion rate is higher than those reported by Rasmussen and Collins (1991) (14.0–21.0%) for a temperate region in USA and Canada, Kong et al. (2005) (7.6%) under Mediterranean climate, Majumder et al. (2008) (14%) for the humid Indo-Gangetic plains of India under irrigated rice-wheat system, Majumder et al. (2007) (5%) for the rice-wheat-jute system and Mandal et al. (2007) (6.4%) for subtropical regions in India. The present study also indicates that the critical amount of C input into the soil is 1.1 Mg C ha^{-1} year^{-1} in Vertisols for a sorghum-based cropping system. This rate of input of biomass-C is lower than those reported by Kong et al. (2005) (3.1 Mg ha^{-1} year^{-1}) for Davis, CA, Majumder et al. (2007) for rice-wheat-jute (*Corchorus spp.* L.) system (4.6 Mg ha^{-1} year^{-1}), Majumder et al. (2008) for irrigated rice-wheat systems of the Indo-gangetic plains (3.6 Mg ha^{-1} year^{-1}) and by Mandal et al. (2007) for rice-based system in subtropical regions of India (2.9 Mg ha^{-1} year^{-1}). A lower rate of input of biomass-C needed to maintain the SOC stock under the present study may be due to lower initial SOC levels (3.5 g kg^{-1} of mean profile SOC concentration) (Srinivasarao et al., 2006). There were 3 to 6 times higher SOC concentrations (>6–15 g kg^{-1}) in soils of the studies reviewed above. The average SOC concentrations in the Indian Himalayan region ranged from 24.3 g kg^{-1} in cultivated soils to 34.5 g kg^{-1} in undisturbed soils (Lal, 2004).

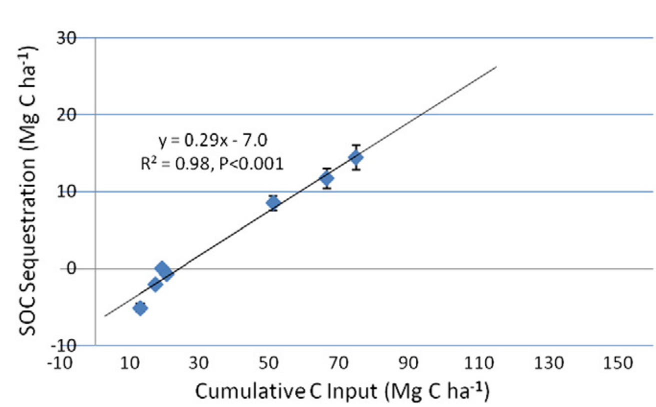

Fig. 6. The level of critical C input to maintain SOC stock at the initial level (error bars represents the standard error of mean for sequestrated C).

4. Conclusion

The data presented support the conclusion that a regular input of biomass-C along with chemical fertilizers is essential to improving soil quality in the semi arid tropics of India, and for minimizing the depletion of SOC stock under continuous cropping. The use of chemical fertilizers at the recommended rate can maintain the SOC level in Vertisols cultivated to a sorghum-based cropping system. A higher SYI of sorghum was obtained with the use of organic amendments (i.e., FYM/sorghum CR/*Leucaena* clippings) along with the use of chemical fertilizers. Use of organic amendments is essential to obtaining higher yields and enhancing the SOC sequestration. The minimum input of 1.1 Mg C ha^{-1} $year^{-1}$ is needed to maintain SOC at the initial level (with no change). However, availability of 4.5 Mg ha^{-1} $year^{-1}$ of FYM (equivalent to 25 kg N) on dry weight basis is a major challenge. Green leaf manuring from *Leucaena* clippings is also a labor-intensive practice. Therefore, use of crop residues along with 25 kg N as chemical fertilizers is a viable alternative for maintaining SOC stock and sustaining crop production.

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